

Final Report for Grant NAG 5-11036
“STUDIES OF COSMIC RAY MODULATION AND ENERGETIC PARTICLE PROPAGATION IN TIME-
DEPENDENT 3-DIMENSIONAL HELIOSPHERIC MAGNETIC FIELDS”

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The primary goal of this project was to perform theoretical calculations of propagation of cosmic rays and energetic particles in 3-dimensional heliospheric magnetic fields. We used Markov stochastic process simulation to achieve to this goal. We developed computation software that can be used to study particle propagation in, as two examples of heliospheric magnetic fields that have to be treated in 3 dimensions, a heliospheric magnetic field suggested by Fisk (1996) and a global heliosphere including the region beyond the termination shock. The results from our model calculations were compared with particle measurements from Ulysses, Earth-based spacecraft such as IMP-8, WIND and ACE, Voyagers and Pioneers in outer heliosphere for tests of the magnetic field models. We particularly looked for features of particle variations that can allow us to significantly distinguish the Fisk magnetic field from the conventional Parker spiral field. The computer code will eventually lead to a new generation of integrated software for solving complicated problems of particle acceleration, propagation and modulation in realistic 3-dimensional heliosphere of realistic magnetic fields and the solar wind with a single computation approach.

At the time of this report, we have essentially completed all the tasks stated in our original proposal. The codes that incorporate an MHD global heliosphere and Fisk-type magnetic field have produced several significant results. The following is summarized in terms of achievement on the topics we have investigated using the cosmic ray modulation codes.

We have investigated of cosmic ray modulation near or beyond the termination shock. This is towards the understanding the Voyager observation of cosmic ray modulation in the outer heliosphere. We first started with a simple model of the heliosheath where the plasma speed is subsonic, divergence-less and spherically symmetric. This is used to verify our calculation method. Once the code is fully understood, we incorporated a global 3-d heliosphere model from a full MHD calculation done by a Co-I, Timur Linde of University of Chicago. With these codes, we found the true mechanisms that lead to cosmic ray modulation in the region beyond the termination shock. We have also made some prediction of cosmic ray flux in various regions of the heliosphere. (a) Due to the diffusion nature of particle transport cosmic rays are modulated by the heliosheath. Cosmic rays arriving at any point outside the termination may have spent significant amount of time inside the termination shock where the solar wind is supersonic and radially expanding. These particles can lose a significant amount of energy by traversing through the supersonic solar wind, thus causing their flux to be modulated by the solar activity. This mechanism could be use to explain why Voyager is still seeing modulated cosmic ray fluxes at locations very close to the expected termination shock. (b) We predict that even after the spacecraft passes the termination shock we will still not see the true interstellar cosmic ray spectrum because the modulation inside the termination shock still affects the cosmic ray flux outside. In one of our calculations, we found no dramatic change of cosmic ray flux across the termination shock. (c) Unlike its behaviors in the inner heliosphere (Ulysses observed a nearly

symmetric distribution of cosmic ray flux <5 AU), the radial gradient of cosmic ray flux in the outer heliosphere depends on heliographic latitude and phase angle relative to interstellar medium speed. (d) The termination shock can have significant acceleration effects on Galactic cosmic rays. The effect is more for high-energy cosmic rays than low-energy cosmic rays. In some cases, the acceleration effect is large enough such that the high-energy cosmic ray flux in certain regions of the heliosphere can be higher than its interstellar level. (e) Low-energy cosmic rays are more sensitive to modulation than acceleration by the termination shock. (f) Gradient/curvature drift is still important to cosmic ray modulation in the outer heliosphere. The cosmic ray flux still depends on the polarity of solar magnetic field and the tilt angle of the heliospheric current sheet. (g) Latitudinal gradient of flux in the outer heliosphere is not necessarily correlated with the polarity of solar magnetic field. We published a paper in the proceedings of the 28th Cosmic Ray Conference. The results were also presented at 2003 AGU fall meeting. An expanded version of the paper has been accepted for publication in *Astrophysical Journal*.

We have also investigated the effect of the Fisk magnetic field model on cosmic ray modulation. The Fisk model theorizes that differential rotation of the footpoints of magnetic field lines on the surface of the sun can cause field lines to become much more twisted than predicted in the Parker model, causing a large deviation of the magnetic field, primarily in the polar region. This can affect the magnitude of the gradient/curvature drift, as well as introducing stronger non-radial elements to the overall drift path. It also affects the parallel vs. perpendicular diffusion in this region. Early results from our adaptation of this model show good agreement of our spectra with those shown in Burger and Hitge (incidentally, we use the magnetic field model that they present). Particles that primarily enter the heliosphere from the poles show significant deviation in spectra when run in a Parker spiral vs. this newer hybrid Fisk field. Particles that come in from the current sheet show a much smaller deviation as a function of the model. We do see a difference even in these spectra however, which is likely due to the fact that our stochastic particles tend to sample the volume of the heliosphere as they diffuse throughout, thus they will be influenced by regions of the heliosphere in which the difference between the Parker and Fisk fields are more pronounced than the current sheet. We are also in the process of analyzing latitudinal gradients and 27 day variation. Very preliminary results disagree with the 27 day amplitude vs. latitudinal gradient relation seen in Burger and Hitge. We seem to see little variation over a rotation period for the parameters used in their model. Further work on this model is ongoing, and we expect more results in the near future.

In the preparation work leading to the full modulation codes, we performed some studies of fundamental particle transport mechanisms in the heliospheric magnetic field. In most previous modulation, the effect of gradient/curvature drift has been always predicted much stronger than what is inferred from the observations, particularly in the polar region, where the regular drift speed of high-energy cosmic rays can exceed the speed of light. This is due to the breakdown of drift approximation. We made calculation of particle drift with higher order drift approximation, resulting in somewhat smaller drift speed. The calculation was further confirmed with numerical particle orbit tracing method. Furthermore, we have also studied the effect of magnetic turbulence on particle drift. With an input of 20% 2-d turbulence and 80% slab turbulence, we can reduced the drift speed by at least by $\sim 50\%$. In all our simulations of particle drift, the reduction of particle drift from its first-order drift approximation is found to be rigidity

dependent, which give a theoretical support to a common practice used by the South African group (Potgieter and his colleagues) to fit cosmic ray observations. The work was presented in 2002 and 2004 December AGU meetings. A paper has been submitted to Journal of Geophysical Research, but due to some disagreement with the referees the paper has not been accepted. We plan to make improvement and resubmit it.

We have also performed additional theoretical studies of cosmic ray modulation by global merged interaction region (GMIR) in the outer heliosphere. We found that the effect of GMIR on cosmic rays does not disappear even after the GMIR exits from the termination shock. If a GMIR modulation model does not include the heliosheath, it may underestimate the recovery time after the GMIR passage. The underestimate is more obvious in the outer heliosphere than in the inner heliosphere. We presented this work at 2004 COSPAR meeting. A formal paper is planned.

In addition to our theoretical effort, we have done great deal amount work on analyzing cosmic ray and heliospheric energetic particle data from various heliospheric missions. This part of work has been quite fruitful. We have produced the following results, most of which have been published in well-known journals:

- (a) Analyze Ulysses observations of cosmic rays during the fast latitude scan in 2000-2001. Determine latitude gradient of cosmic rays at solar maximum.
- (b) Use solar energetic particle anisotropy to determine the perpendicular to parallel ratio of the diffusion coefficient. Discover the importance of perpendicular diffusion in the transport of solar energetic particles.
- (c) Analyze Voyager energetic particle observations at large radial distance of 85-90 AU. Determine the uncertainty of the solar wind speed. Give an alternative explanation to the anisotropies observed by LECP on Voyager 1. The 2002 Voyager observations of low-energy particles, after the correction of additional background subtraction, is more consistent with upstream particles from the termination shock.
- (d) Analyze jovian relativistic electrons measured by Ulysses in its 2004 distant encounter with Jupiter. Determine particle diffusion coefficient in the inner heliosphere and jets of jovian electrons.

In summary, we have achieved or, more precisely, exceeded our main goals outlined in our proposal. The major part of work, the development of a comprehensive code of cosmic ray modulation in the heliosphere, has been completed. Results of model runs are new and encouraging. The code has opened up many new opportunities to look at the modulation of cosmic rays using various kinds of models. Our data analysis efforts have produced great results in understanding particle transport in the heliosphere. For future work, we will target our models towards new observations from the heliospheric network missions.

Papers produced under full or partial support of this grant

1. "Galactic Cosmic Ray Modulation Using a Solar Minimum MHD Heliosphere: A stochastic Particle Approach", Ball, B., Zhang, M., Rassoul, H., Linde, T., *Astrophys. J.*, in press, 2005
2. "The Compton-Getting Effect of Energetic Particles with an Anisotropic Pitch-Angle Distribution", Ming Zhang, *Adv. Space Res.*, 35, issue 4, 562, 2005.
3. "The Compton-Getting Effect of Energetic Particles with an Anisotropic Pitch-Angle Distribution: An Application to Voyager 1 Results at ~85 AU", Ming Zhang, *Astrophys. J.*, 624, 1038, 2005.
4. "Energetic Particles at High Latitudes of the Heliosphere", Zhang, Ming, *Physics of the Outer Heliosphere*, AIP Conference Proceedings, Vol. 719, V. Florinski, N. V. Pogorelov, and G. P. Zank. Melville, NY: American Institute of Physics, p.260-265, 2004.
5. "Perpendicular transport of solar energetic particles in heliospheric magnetic fields", Ming Zhang, J.R. Jokipii, and R.B. McKibben, *Astrophys. J.*, 595, 493, 2003.
6. "Ulysses COSPIN Observations of Cosmic Rays and Solar Energetic Particles from the South Pole to the North Pole of the Sun during Solar Maximum", R.B. McKibben, J.J. Connell, C. Lopate, M. Zhang, J.D. Anglin, A. Balogh, S. Dalla, T.R. Sanderson, R.G. Marsden, M.Y. Hofer, H. Kunow, A. Posner, B. Heber, *Ann. Geophys.*, 21, 1217-1228, 2003
7. "Ulysses Observations of Solar Energetic Particles From the July 14 of 2000 Event at High Heliographic Latitudes", Ming Zhang, R. B. McKibben, and C. Lopate, J. R. Jokipii and J. Giacalone, M.-B. Kallenrode, H. K. Rassoul, *J. Geophys. Res.*, 108, 1154, 2003.
8. "Modulation of galactic cosmic rays at solar maximum: observations", Ming Zhang, *Adv. Space Res.* 32, 603-614, 2003.
9. "Modulation Near Solar Maximum at High Solar Latitudes: Observations From the Ulysses Cospin High Energy Telescope, R. B. McKibben, C. Lopate", and Ming Zhang, *Space Science Reviews*, v. 97, 367-371, 2001.
10. "Simultaneous Observations of Solar Energetic Particle Events by imp 8 and the Ulysses Cospin High Energy Telescope at High Solar Latitudes", R. B. McKibben, C. Lopate, and Ming Zhang, *Space Science Reviews*, v. 97, 257-262, 2001.
11. Perpendicular Diffusion and Drift of Solar Energetic Particles in Heliospheric Magnetic Fields, M. Zhang, J.R. Jokipii and R.B. McKibben, *Proc. 28th ICRC*, 3495-3498, 2003
12. Modulation of Galactic Cosmic Rays near and beyond the Termination Shock, B. Ball and M. Zhang, *Proc. 28th ICRC*, 3839-3842, 2003

Presentations at Meetings

1. "Uncertainties of Solar Wind Speed Determination Using Voyager Energetic Particle Anisotropy Measurements at 85 AU", Ming Zhang, American Geophysical Union, Fall Meeting 2004, abstract #SH41B-06
2. "The Gradient/Curvature Drift of Cosmic Rays in the Heliospheric Magnetic Fields with Turbulence", Ball, B. M.; Zhang, M.; Qin, G.; Rassoul, H., American Geophysical Union, Fall Meeting 2004, abstract #SH43A-1099

3. "The effect of adiabatic energy loss on the parallel mean free path of solar energetic particles", Qin, G.; Zhang, M.; Dwyer, J. R.; Rassoul, H. K., American Geophysical Union, Fall Meeting 2004, abstract #SH53B-0318
4. "Modulation of cosmic rays in the outer heliosphere at solar maximum", Zhang, M.; Ball, B., 35th COSPAR Scientific Assembly. Held 18 - 25 July 2004, in Paris, France., p.2079
5. "The Compton-Getting effect for an anisotropic pitch angle distribution of energetic particles", Zhang, M., 35th COSPAR Scientific Assembly. Held 18 - 25 July 2004, in Paris, France., p.2080
6. "Anisotropies of anomalous and galactic cosmic rays upstream and downstream of the termination shock", Zhang, M.; Ball, B.; Qin, G.; Rassoul, H., American Geophysical Union, Fall Meeting 2003, abstract #SH12C-07
7. "Modulation Near the Termination Shock: Stochastic Particle Studies using an MHD Heliosphere", Ball, B. M.; Zhang, M.; Rassoul, H.; Linde, T., American Geophysical Union, Fall Meeting 2003, abstract #SH11C-1109
8. "Perpendicular transport of solar energetic particles: Ulysses observations at high heliographic latitudes", Zhang, M.; McKibben, R. B.; Jokipii, J. R.; Rassoul, H. K., American Geophysical Union, Fall Meeting 2002, abstract #SH72B-05
9. "Second Order Correction to the Gradient/Curvature Drift Term of Cosmic Ray Transport in Heliospheric Magnetic Fields", Ball, B. M.; Zhang, M., American Geophysical Union, Fall Meeting 2002, abstract #SH71A-02
10. "Cosmic ray modulation at the solar maximum: Ulysses observations during the fast latitude scan of the inner heliosphere", Zhang, M.; McKibben, R. B.; Lopate, C., American Geophysical Union, Spring Meeting 2002, abstract #SH51A-07